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SHADE DESIGN IN SPAIN: HOW TO PROTECT AGAINST HEAT AND UV-RADIATION

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Summary: Shade design is a new discipline that was originally developed in Australia and New Zealand, where high rates of skin cancer have been a key factor driving innovation. It combines climatic comfort under shading structures with ultraviolet (UV) protection. Some modern fabrics heat up rapidly when exposed to strong sunlight and offer poor protection against UV-radiation. Precise information about the properties of shading materials is scarce and norms used in solar protection are not adapted to the field of tension membrane structures.

1 INTRODUCTION

In southern Europe shade is the basic requirement for thermal comfort in the exterior. Natural as well as built shade permit outdoor living in a Mediterranean climate during most of the year. Alleys, arcades, pergolas and of course *toldos* and textile canopies protect the human being from direct and diffuse solar radiation. Indeed, textile shading has a 2000 year history in Spain, producing highlights such as the *Roman Velum*, the *Andalusian Toldo* and the *Catalan Envelat*. Surprisingly, this rich tradition has not generated a solid line of academic research. Very little information and nearly no literature is to be found about the climatic comfort and the UV-protection characteristics of a horizontal membrane structure. For example, an analysis of existing shading canopies shows that the main criterion for colour selection is purely aesthetical. Usually it fits into an overall design scheme or just repeats the colours of an associated commercial logo. And if the logo happens to be black, the shading material might just follow suit. This raises a number of basic questions which have not been properly answered: How big is the difference in comfort underneath two differently coloured fabrics? Do brighter colours really lead to a higher degree of climatic comfort than darker ones? Does the selection of material or coating make a difference?

2 WARM SHADE

Warm shade makes sense in a cold climate. It allows UV-radiation filtering and provides heat through a combination of transmitted and absorbed solar energy. In a Mediterranean climate, warm shade should therefore be avoided with the possible exception of the winter months.

Figure 1: Photo of a bicolour acrylic fabric and Figure 2: Infrared image of the same fabric showing clearly the difference in temperature between the dark blue and the white stripes. The latter ones are much cooler.

Dark colours absorb most of the solar radiation leading to higher temperatures and to a higher heat emission from the fabric. Following the Stefan-Boltzmann law, the total heat flux in watts produced by thermal radiation depends on the surface temperature raised to the power of four and can be calculated according to following formula:

$$P = \varepsilon_i \times A \times \sigma \times T_i^4 \qquad (1)$$

[ε_i] is the emissivity of the underside surface of the membrane panel, [A] is the total surface area, [σ] is the Stefan- Boltzmann constant [$5.6697\times10^{-8} W/m^2\ K^4$] and [$T_i\ ^4$] is the underside surface temperature in Kelvin raised to the power of four

The uncritical application of the *solar factor* (g-value) suggests that dark colours combined with low solar transmission automatically lead to a higher degree of climatic comfort. This false assumption might explain why manufacturers and designers favour dark colours for acrylic canopies. A good example of this mindset is the following comment made by a the Austrian shade designer Gerald Wurz that appeared in the leading German web data base dedicated to construction, expertise and built objects, www.baunetzwissen.de: "*It is untrue that climatic comfort is higher underneath a bright fabric than underneath a dark one, says the designer. The (African) Touaregs…already knew this for centuries*"[1]. The author ignores that dark pigments were traditionally the only way to protect textile fibres from rapid deterioration under UV-radiation. The same mechanism protects the human body: a dark skin absorbs more solar energy in order to avoid a deeper penetration into the epidermis and a subsequent DNA damage. In both cases a higher level of protection is achieved at the price of a lower level of climatic comfort.

3 COOL SHADE

The tightening of building codes for isolation in northern Europe has led investigators to focus generally on the subject of membrane enclosures. However, the specific problem of open shading structures in southern countries has not been well investigated. The recently presented thesis *Cool Shade Tents* [2] tries to fill this gap and expand knowledge of comfort and protection under light-weight membranes. Cool shade is suitable when temperature and UV-radiation levels are high. Materials should block both of them in order to improve summer cooling and UV-protection. The thermo-dynamic behaviour of 20 different materials has been investigated and extensive outdoor testing been carried out under Spanish summer conditions. The aim was a comparative assessment and classification of the selection.

4 THERMAL HEAT TRANSFER IN TEXTILE MEMBRANES

Shading materials are exposed to strong solar radiation, which includes UV, visible light (VIS) and near infrared radiation (NIR). They also receive a spectrum of mid-infrared radiation (MIR) that corresponds to the level of heat emission of the surrounding terrestrial objects. The three mechanisms of thermal heat transfer on earth are *conduction*, *convection* and *radiation*. Convection and conduction are slow mechanisms and need either a medium of thermal transport or a direct contact between objects. Only electromagnetic radiation from 0,1µm to 1000µm conveys thermal energy in forms of photons even through the vacuum of cosmic space.

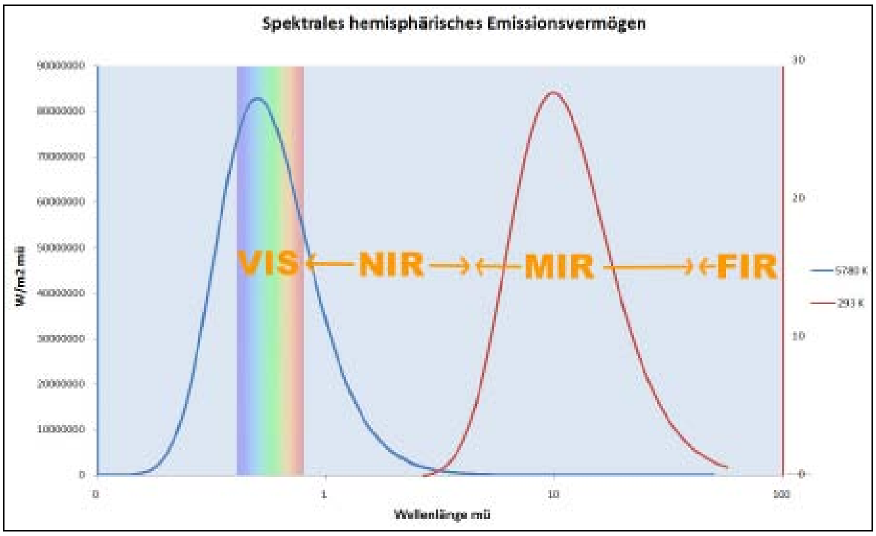

Figure 3: Hemispheric emission power of the sun (5780K, blue line) and a terrestrial object radiating at +20ºC (293K, red line). The blue and red ordinate axes relate to the correspondingly coloured lines. The abscissa axis shows the wavelength in micrometre (µm) and follows a logarithmic scale. The sun radiates mostly in the visible region (VIS) at a wavelength of 0,38-0,78µm and reaches its maximum in the green spectrum. Terrestrial objects radiate at a wavelength of 3,0-50µm in the mid-infrared spectrum (MIR). Their maximum emission power lies in the range 8-13µm and can be captured by an infrared camera. NIR refers to the near-infrared range 0,78-3,0µm and FIR to the far-infrared spectrum from 50-1000µm.

Textile membranes have a weight of around 1kg/m² and a thickness of less than a millimetre. Their skin-like quality makes them highly responsive to any fluctuation in received energy. Traditional concepts such as thermal capacity or conductivity cannot explain their thermal behaviour, which is entirely dominated by radiation and convection. Any change of temperature on one side is immediately passed to the other. The sun radiates from the photosphere at a temperature of around 5780K, which leads to a fairly constant solar radiation at the entry of our atmosphere of about 1360W/m². We tend to forget that without the filter of our atmosphere the temperature under bright sunshine would rise to 130ºC, as is the case on the moon.

5 IN SITU MEASUREMENTS

As part of the research undertaken for the thesis *Cool Shade Tents*, a horizontal shading device was constructed in 2009 to quantify the thermo-dynamic behaviour of twelve different shading samples. A data logger saved the temperatures measured by nine PT-100 thermocouples every two minutes, as well as the maximum and minimum values occurring over an interval of 30 minutes. The results were double checked by the parallel use of a professional infrared camera. The camera also made it possible to include three natural shading materials that could otherwise not have been monitored. Measuring temperatures of a thin, skin-like membrane is a delicate procedure. Thermocouples always add mass to the studied membrane and an open mesh lets sunrays pass directly to them right through the openings. Both cases lead to erroneous results. On the contrary, infrared cameras permit temperature measurement without contact, although they do encounter problems with low-emissivity (low-e) treatments and heat reflective surfaces. Using a combination of the two measurement methods, however, produces accurate results. Special care was taken to limit the influence of convection on the comparative study by choosing only days with conditions of bright sunshine, no clouds and little air movement. The total solar radiant flux was recorded with the help of an *albedometer*. It captured the direct and diffuse parts of the solar radiation from above as well as the reflected parts from below. Knowing the solar optical properties of the different materials, it was then possible to calculate the transmitted and reflected parts of the solar flux. It was also necessary to collect the external environmental data such as air temperature, humidity and wind speed in order to correctly assess the results.

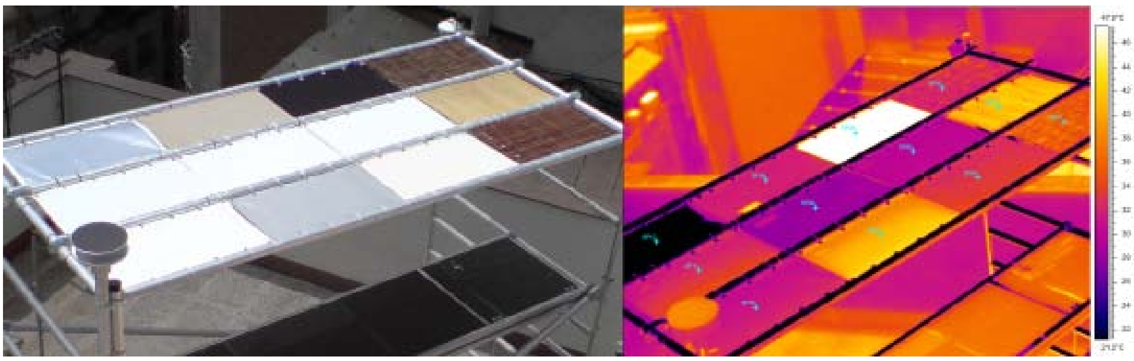

Figure 4 and Figure 5: Photo and infrared images of a horizontal shading device with 12 materials exposed to direct sunlight on top of a high rise apartment block in downtown Barcelona. As part of the research, surface temperatures were measured by means of PT 100 thermocouples and a professional infrared camera.

6 SOLAR OPTICAL PROPERTIES OF TEXTILE MATERIALS AND LOW EMISSIVITY TREATMENTS

Thermal optical properties are a function of three parameters: *reflectance*, *transmittance*, and *absorptance*. These describe the ratio of the reflected, transmitted and absorbed radiant flux to the total radiant flux. According to Kirchoff's law of thermal radiation, which applies to black and grey bodies, the sum of these three parameters is equal to one within any specified waveband of the electromagnetic spectrum.

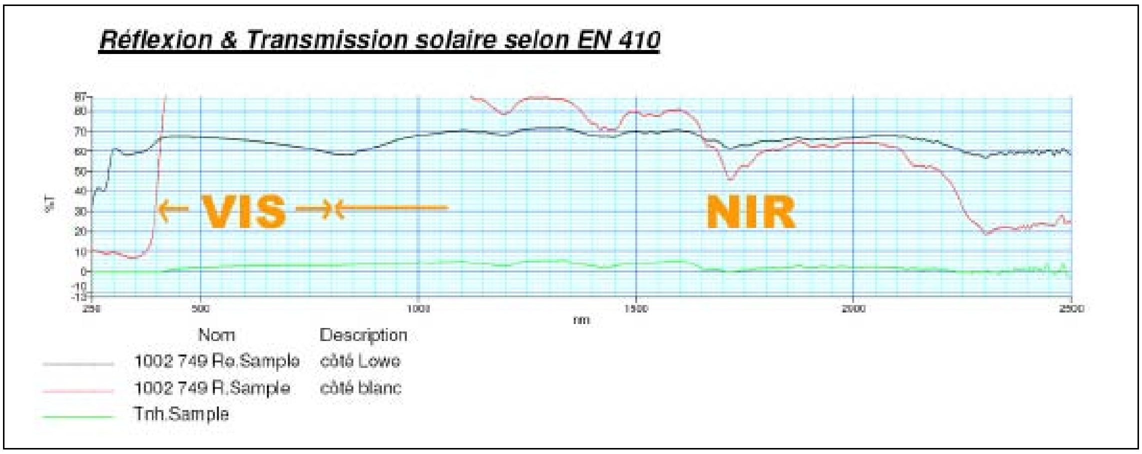

Figure 6: Solar optical properties of a low-e coated polyvinylchloride (PVC)/polyester 1002 fabric membrane measured in the laboratory of Ferrari SA in France. The values of reflection and transmission are directly measured whereas the absorbed part of the thermal energy has to be calculated using Kirchhoff's law. The upper white side of the membrane should point to the sky while the low-e side (treated with nanoparticles of aluminium) should be directed to the earth. The red line shows the reflection of the white side ("côté blanc") and the black line the reflection of the low-e treated surface ("côté Lowe") in a wavelength from 250 to 2500nm. The red line has an optimum of reflection in the visible spectrum (VIS) whereas the black line shows a fairly constant reflection rate between 60-70%. The green line shows the value of solar transmission.

White fabric reflects most of the solar radiation in the visible spectrum (VIS), somewhat less in the near-infrared range (NIR) and absorbs nearly all radiation in the mid infrared range (MIR). A horizontal white membrane therefore combines a high reflection in the short wave spectrum with a maximum loss of heat in the mid-infrared range. This is a great advantage for cool shade tents during summer, but poses serious problems for membrane enclosures in winter.

Today it is possible to manufacture a fabric with specific values of reflectance, transmittance and absorptance in the different wave bands of VIS, NIR and MIR. Low-emissivity coatings made out of aluminium, silver or *tinox* (titan-nitrit-oxyd) help to reflect thermal radiation in the mid-infrared spectrum. It is important that the coating is applied on the reverse side to the sun, because a white colour reflects much better in the visible spectrum than a metalized surface. *Tinox* coatings are typically used for solar collectors: their dark colour (titan) together with a selective low-e capacity in the mid-infrared range acts as a heat trap for solar energy. The application of this technique on dark acrylic fabric (commercially called *Cold Black*) leads unquestionably to warm rather than cool shade.

7 MEASURED RADIANT FLUX OF HORIZONTAL MEMBRANES COMPARED TO CALCULATED SOLAR FACTOR (G-VALUE)

The following diagram shows the balance of received and emitted radiation (assuming air movement is limited to natural convection). Four main sources of radiant power or radiant flux in Watt need to be considered underneath a horizontal shading structure:

1. The reflected solar albedo [Φ_{albedo}] radiation (VIS and NIR)
2. The transmitted part [Φ_T] of global solar radiation (VIS and NIR)
3. The radiant flux [Φ_E] of the fabric (MIR)
4. The reflected infrared radiation [Φ_{back}] of the surrounding objects (MIR)

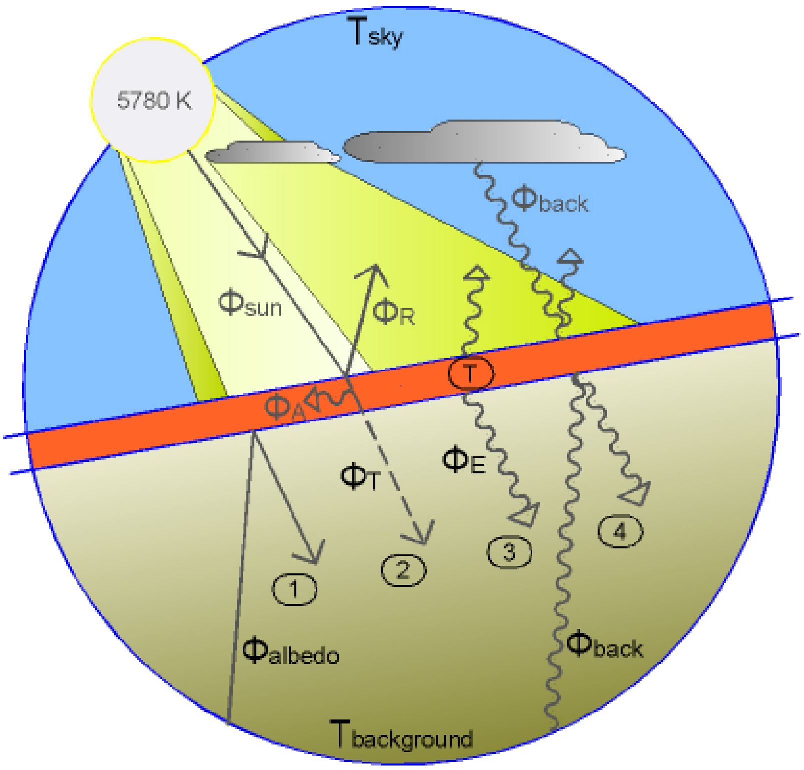

Figure 7: Diagram reproduced from the thesis *Cool Shade Tents* showing four sources of radiant flux underneath a horizontal membrane. [Φ_T] is the reflected and [Φ_A] the absorbed part of the global solar radiation. [T] is the temperature of the underside of the membrane. The temperature of the sky [T_{sky}] typically reaches -20ºC at noon during the summer months in Barcelona. [$T_{background}$] is the resulting mean temperature of the surrounding terrestrial objects.

The Solar Factor (g-value, European norm *EN 410:1998*) consists of two parts, which together express the permeability of a vertical glass pane to diffuse solar radiation on a cloudy day. However, it is a norm that is based on the specific case of a highly transparent and vertical piece of glass, and incorporates only two of the four radiant sources treated in figure 7:

1. The transmitted part [Φ_T] of the global solar radiation (VIS and NIR)
2. The secondary part [q_i] of the absorbed solar heat flux (MIR)

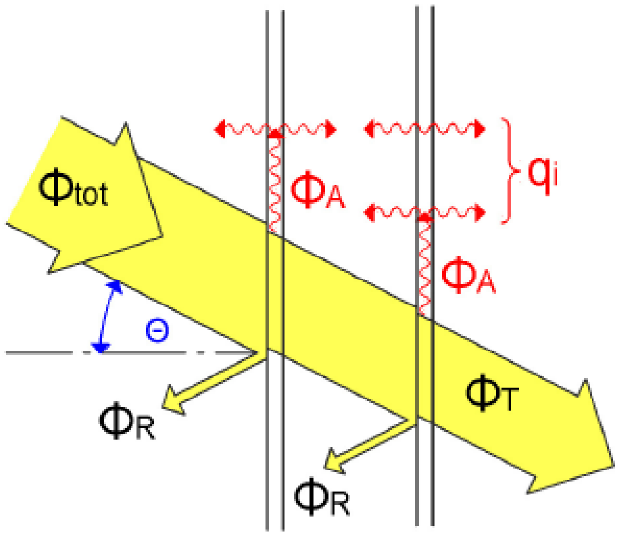

Figure 8: Diagram of the g-value (European Norm *EN 410:1998*) applied to vertical double glazing with a high degree of transparency in the visible range. R stands for reflection, T for transmission and A for absorption.

The incoming solar flux multiplied by the g-value calculates the amount of solar energy entering a confined space. This gives an erroneous result in the case of an open and horizontally disposed shading device, mainly because it totally neglects the heat radiation of the membrane itself.

The norm *EN 410:1998* is based on the assumption that a transparent glass pane never heats up to a degree where the radiant flux exceeds the transmitted part of the solar energy. However, this is simply not the case for most shading structures. Neither does the norm consider additional heat sources such as albedo radiation or the heat flux of surrounding terrestrial objects. The application of the norm leads directly to the mistaken preference of dark coloured fabrics in textile canopies.

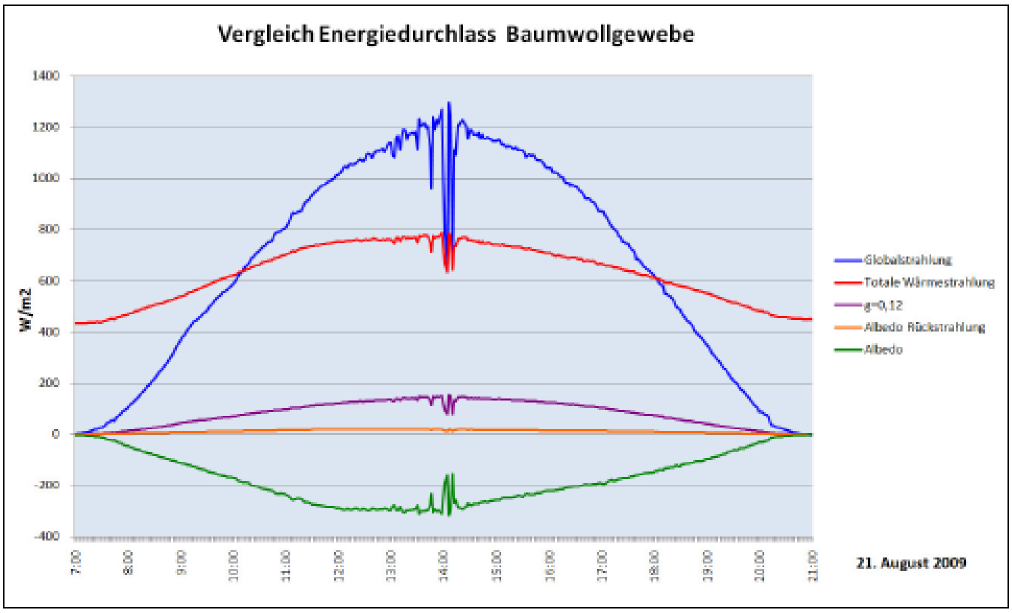

Figure 9: Measurements taken in Barcelona on August 21, 2009 at local summer time (14:00 local time is 12.00 in coordinated universal time).The blue line shows the global solar radiation and the green line the albedo radiation from below the horizontal cotton membrane. The violet line results from the multiplication of the calculated g-value of 0,12 with the measured global solar radiation. The red line shows the total heat flux for the lower side based on the four sources of radiant power explained in figure 7. It becomes obvious, that the red and the violet line have little to do with each other.

8 UV-PROTECTON UNDER SHADING STRUCTURES

The spectrum for ultraviolet radiation ranges from 1-380nm. Extreme UV (EUV), vacuum UV (VUV) and UV-C-radiation do not pass the barrier of the atmosphere. UV-B in the wavelength from 280-315nm is therefore the most energetic and potentially dangerous radiation reaching the earth. UV-A radiation from 315-380nm is equally harmful for the human being because it penetrates deeper into the epidermis. The international Agency for Research on Cancer (IARC), part of the World Health Organization (WHO), determined in 1992 that both types of ultraviolet radiation can produce different forms of skin cancer. In order to enjoy the positive effects of solar radiation and limit the negative ones, dermatologists recommend providing shade in summer during the critical time frame of two hours before and two hours after solar noon. Children and adolescents are in particular need of protection as their skin is still not fully developed. Both groups pass lots of time outdoors. Australia and New Zealand suffer the highest rates of skin cancer in the world because the effect of strong solar radiation of the austral summer is multiplied by a huge ozone hole, and the skin of descendants of white Europeans is typically not prepared for the solar radiation of the antipodes. With great success local authorities have converted shade design into a public health issue. In 1996 both countries introduced the ultraviolet protection factor (UPF) as a classification system of textile fabrics that are in direct contact with the skin.

UPF CLASSIFICATION SYSTEM

UPF Range	UVR protection category	Effective UVR transmission, %	UPF Ratings
15 to 24	Good protection	6.7 to 4.2	15, 20
25 to 39	Very Good protection	4.1 to 2.6	25, 30, 35
40 to 50, 50+	Excellent protection	≤2.5	40, 45, 50, 50+

Table 1: The ultraviolet protection factor (UPF) classifies [3] the transmission of ultraviolet radiation: In order to achieve a "*good protection*", a minimum of 93,3% of the incoming UV-radiation has to be reflected or absorbed. The classification was developed originally for clothing. The values for a horizontal shading structure should be generally much lower because of the effect of scattered and reflected UV-radiation.

An excellent protection (40, 50, 50+) means an effective ultraviolet transmission of less than 2,5%. A horizontal shading structure can never reach this level of protection, because scattered and reflected UV-radiation keeps penetrating from all open sides. Dense fabrics and pigmented textiles offer more protection than open meshes and permeable fibres. The formula for calculating UPF is given below:

$$UPF = 100 / \tau \qquad (2)$$

The value of UV-transmission [τ] is introduced as a percentage. All transmission values below 2% are considered "best" [50+].

9 CONCLUSIONS AND RECOMMENDATIONS

Children and adolescents are generally not aware of the full dangers of over exposure to the sun. Courtyards, patios, playgrounds and public spaces in general need to be protected. Shade audits should be the basis of shade design projects that effectively combine natural with built shade. Designers use mainly tensile membrane structures for built shade because they combine lightweight with cost efficiency and ease of erection. The results of this research lead to the following eight-point summary of what should be good practice in climatic comfort and UV-protection under horizontal membrane structures:

1. The use of highly reflective, white fabric is the first and best option to minimize absorbed solar heat. White *Teflon* (PTFE) stands out as a particularly efficient fabric because it repels dirt and maintains its original solar optical properties.

2. Heat losses to the open sky should be as high as possible. Even under a burning sun a horizontal membrane can still lose up to 200W/m² of heat to the sky. White fabrics have excellent selective properties for shading purposes: they are white in the visible spectrum and appear black in the mid-infrared range, thus losing a maximum of heat to the cold blue sky.

3. Small shading structures exposed to high solar albedo radiation from below should combine a white side to the sun with a dark or even black side to the earth. The dark side avoids short wave solar reflection and leads to a lower total heat flux.

4. Low-e coatings on the inner side of membranes help to keep thermal radiation as low as possible. However, when applied to the upper side of the fabric, such coatings would prevent the intended heat loss to the sky and lead to higher temperatures.

5. The transmitted part of solar energy should be minimized. Small canopies should be completely opaque as there is enough light entering from the open sides.

6. Textile membranes are not in direct contact with the skin, so the highest possible ultraviolet protection factor should be chosen.

7. There is a direct relationship between the size of the visible part of the sky seen from underneath a shading structure to the diffuse and scattered UV radiation received. It is not enough to block only the direct solar radiation. Open sides have to be reduced and duly protected. For example, the classical *hypar*-shaped sail fails to offer the required protection around its high points.

8. Natural shade creates a higher degree of thermal comfort than built shade because plants regulate their temperature through evaporation and the use of solar energy in photosynthesis. It is highly recommended to combine natural and built shade in order to maximize the advantages of both systems.

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